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13. ABSTRACT *(Maximum 200 words)*

The aims of this research are (i) To study the multidimensional spatio-temporo-chromatic signal processing capabilities of visual receptive fields. (ii) To identify the key attributes of multidimensional image signals which are sensitive to receptive field filters and how these attributes are transformed for encoding beyond the receptive fields.
By using digitized sequences of natural images, formulating a representation for natural images, and incorporating properties of specialized visual receptive fields and neural pathways we (i) Propose a model of how the early visual system efficiently codes natural time varying images, first by tracking part of the image, then by matching the spatiotemporal properties of the neural pathway to those of the tracked image. We also propose that retinal architecture which varies with eccentricity also matches the properties of the tracked image. (ii) Develop a new model for signal propagation through multiple cell layers in the retina which can incorporate the different cell densities in retinal cell layers. (iii) Propose that visual color receptive fields are matched to the spatio-chromatic structure of natural color images.

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Multidimensional Signal Coding in the Visual System
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(due date 11/30/92)

1. STATUS OF THE RESEARCH

The aims of this research shortly recapitulated are:

(i) To study the multidimensional spatio-temporo-chromatic signal processing capabilities of visual receptive fields

(ii) To identify the key attributes of multidimensional image signals which are sensitive to receptive field filters and how these attributes are transformed for encoding beyond the receptive fields.

Cited below are abstracts of papers published, in press, or submitted which summarize the research. Full citation locations are given in Section 2. The abstracts are given in related groups and can be disseminated as such.

A. Spatiotemporal Coding

A.1. Efficient Coding of Natural Time Varying Images in the Early Visual System

We investigate the hypothesis that the early visual system efficiently codes natural time varying images, first by tracking part of the image, then by matching the spatiotemporal properties of the neural pathway to those of the tracked image. A representation for the time varying image is formulated which consists of two spatiotemporal components, a velocity field component and a stationary component. We show, using digitized sequences of natural images, that the spatiotemporal spectrum and other attributes of the image markedly differ before and after tracking. The temporal frequency bandwidth and velocity distribution of the velocity filed component are diminished in the region of tracking and broaden with increasing eccentricity from this region. On the other hand, the spectrum of the stationary component is unaffected by tracking. Comparison of the properties of the tracked image to those of the M and P pathways in the visual system suggests that each pathway transmits different attributes of the tracked image. A retinal architecture which varies with eccentricity also matches the properties of the tracked image.

A.2. Separability of Spatiotemporal Spectra of Image Sequences

We calculated the spatiotemporal power spectrum of 14 image sequences in order to determine the degree to which the spectra are separable in space and time, and to assess the validity of the commonly used exponential correlation model found in the literature. We expand the spectrum by a Singular Value Decomposition into a sum of separable terms and define an index of spatiotemporal separability as the fraction of the signal energy that can be represented by the first (largest) separable term. All spectra were found to be highly separable with an index of separability above 0.98. The power spectra of the sequences were well fit by a separable model of the form:

$$P(k,f) = \frac{ab/(4\pi^3)}{((a/2\pi)^2 + k^2)^{3/2}((b/2\pi)^2 + f^2)}$$

where k is radial spatial frequency, f is temporal frequency, and *a*, *b* are spatial and temporal model parameters which determine the effective spatiotemporal bandwidth of the signal. This power spectrum model corresponds to a product of exponential autocorrelation function separable in space and time.

A.3. The Effect of Tracking Strategies on the Velocity Structure of Image Sequences

We investigate the effect of different tracking strategies, such as local and full field tracking, on the mean and variance of the image velocity field. We show that while local tracking reduces the velocity variability in an eccentricity dependent manner, full field tracking reduces velocity variability equally across the image. We test our prediction with digitized image sequences.

B. Retinal Signal Sampling

B.1. Signal Sampling and Propagation through Multiple Cell Layers in the Retina: Modeling and Analysis using Multirate Filtering

The retina is a multilayered structure. Each layer consists of one or more classes of cells, each at its own density and with its own anatomic and physiologic properties. Signals converge from many cells in one layer onto single cells in another layer, and a signal from a single cell diverges to many cells in the next layer. In this methods paper, we develop a general approach to retinal analysis and modeling that incorporates multiple cell classes, their densities, and related anatomic properties. The method is based on multirate filtering, a branch of signal processing that concerns manipulating signals of different sampling rates. By drawing a correspondence between cell density and signal sampling rate, we incorporate different cell densities, convergence, divergence, variation in dendritic field shape, cell-to-cell variation in synaptic weights, and other anatomic features into multirate models. We develop the multirate approach and apply it to the cat cone $\Rightarrow$ cone bipolar CBb_1 $\Rightarrow$ on-ß ganglion cell pathway as an example. We calculate the spatial frequency responses of the CBb_1 and on-ß cells based on the cone spatial frequency response and find that the attenuation of high frequencies in the cones prevents aliasing that would otherwise occur in CBb_1 and on-ß cells. We compare the calculations with cat psychophysics. We show that the optics of cat eye are insufficient by themselves to prevent aliasing in these cells, additional attenuation by the cone-cone gap junctions and cone aperture are necessary. We demonstrate that the highest spatial frequency that can be passed by the retina without aliasing is not always determined by the densities of cones, bipolar and ganglion cells, but also by the synaptic and dendritic weighting between these cells.

B.2. Conversions Between Parallel and Hierarchic Architecture Analysis Multirate Filter Banks

We derive general conversions between equivalent parallel and hierarchic analysis multirate filter banks (MRB's) as well as sufficient conditions for existence and uniqueness of the conversions. We use MRB's with arbitrary, rational number changes in sampling rate between successive outputs and arbitrary Linear Time Invariant filtering for each output. Conversion consists of commuting sampling rate expanders, sampling rate compressors, and filters to turn on MRB into the form of the other. For a class of MRB's we call "well-formed", the conversions between architectures are one to one.

B.3. Complexity and Filter Memory Requirements in Scaled Gaussian Hierarchic and Parallel Analysis Multirate Filter Banks.

Scaled Gaussian analysis multirate filter banks (MRBs) are analysis MRBs whose filters are Gaussians scaled differently in width and height. They are frequently employed in vision research and image processing. We define generalized scaled Gaussian analysis MRBs for both parallel and hierarchic architectures and derive conversions between them. We calculate the number of multiplications, number of additions, and total number of filter coefficients for both architectures implemented in direct form and time-varying filter implementations. Our results are for both one-dimensional MRBs and two-dimensional MRBs with separate filters. In all cases, as has been shown for particular MRBs, the parallel MRB requires considerably more multiplications, additions, and filter coefficients than the equivalent hierarchic MRB. However, the relative differences are far less severe in the time-varying case. We also examine the influence of the resampling factors on the complexity results. The results for two-dimensional MRBs with separable filters are qualitatively the same as in the one-dimensional case.

C. Spatio Chromatic Coding (Summary)

Neurophysiology provided color research with a wealth of single unit recordings indicating how color is coded in the early visual system. These show that when color is coded in the visual system it is encrypted together with spatial features. Filters (receptive fields) in the visual system have spatial responses with varying spatial frequencies which are modulated by different color (wavelength) profiles. Some combinations occur frequently in the visual system and some are rare or non-existent. An obvious requirement of the coding system is that it be sufficient to contain all image information relevant to the visual system for processing at higher levels of the visual system. One of the most commonly applied hypotheses to understand the coding strategy is that the visual system is an efficient coder and that it is matched to its signal environment which is *natural color imagery*. By decomposing natural imagery to its building blocks we can compare how these are matched by the building blocks of the visual image coding scheme.

The principal components (eigenfunctions) of a group of signals can serve as a basis for that group. The advantages of representing a signal by principal components can be briefly summarized as follows. (i) The basis functions of the representation are orthogonal and have uncorrelated coefficients. (ii) The expected square coefficients (eigenvalues) are minimum compared to other generalized Fourier representations. These properties make principal components attractive for efficient signal coding and representation, because uncorrelatedness reduces redundancy and smaller coefficients require smaller dynamic ranges and hence, less transmission resources. Similar considerations have been used before in identifying the strategy of visual system operations. The eigenfunctions of black and white images are well-known. They include functions with periodic profiles in both spatial dimensions. We extended the analysis of the one-plane black and white images to 3-plane color images.

We computed the principal components of a number of natural color images using small sections of the images. We used 3-D blocks of 4 x 4 pixels in each color plane. The visual system also applies receptive fields which cover small sections of the image. Principal components computed for the natural color images are comprised of basis functions with various spatial and color profiles. These principal components are similar to certain visual system image operations in space and in color, including the color opponent transformation and a variety of spatially organized receptive field filters with different orientations. Color opponent profiles are most prominent in low spatial frequencies and have very low eigenvalues for high spatial frequencies. For example, the fraction of signal energy represented in low spatial frequency color profiles is significant, while the expected signal energy in color profiles with high spatial frequency is negligible. This suggests that color and space are nearly separable when small sections of natural images are considered. This separability diminishes as the size of the sections increase. Another advantage of the small sections is their computational load. The computational load associated with whole images or large sections thereof, in this kind of analysis, is immensely large. We reconstructed the image using the eigenfunctions. We find that the image can be reconstructed from a small number of eigenfunctions which are similar to visual system receptive fields.

2. PUBLICATIONS

"The Spatio-temporal Spectrum of Time Varying Imagery", M.P. Eckert, G. Buchsbaum, A.B. Watson, IEEE Transactions on Pattern Analysis and Machine Intelligence, in press

"Conversion Between Parallel and Hierarchic Architecture Analysis Multirate Filter Banks", B.S. Levitan and G. Buchsbaum. IEEE Transactions on Signal Processing, 40, 2837-2841 (1992).

"Efficient Coding of Natural Time Varying Imagery in the Early Visual System", M.P. Eckert and G. Buchsbaum. Philosophical Transactions of the Royal Society (London) accepted (1993).

"Complexity and Filter Memory Requirements in Scaled Gaussian Hierarchic and Parallel Multirate Filter Banks", B.S. Levitan and G. Buchsbaum, accepted, J. Visual Communication and Image Representation, in press (1993).

"Signal Sampling and Propagation through Multiple Cell Layers in the Retina: Modeling and Analysis Using Multirate Filtering," B. Levitan and G. Buchsbaum, submitted (1992).

"The Relationship Between Retinal Receptor Packing and Tracking Eye Movements," M.P. Eckert and G. Buchsbaum, in preparation (1992).

"The effect of Tracking Strategies on the Velocity Structure of Image Sequences," M.P. Eckert and G. Buchsbaum, in final preparation for submission.

3. RELATED PUBLICATIONS

"Hybrid Spatio-Chromatic Coding in the Visual System", G. Buchsbaum, in Channels in the Visual Nervous System, Neurophysiology, Psychophysics, Models, B. Blum, ed., Freund, London, 139-150 (1991).

"Temporal Differences Between Color Pathways Within the Retina as a Possible Origin of Subjective Color," S.M. Courtney and G. Buchsbaum, Vision Research, 31, 1541 - 1548 (1991).

4. BOOK CHAPTERS

"Visual Systems Considerations in the Coding of Natural Images," G. Buchsbaum, prepared for Visual Factors in Electronic Image Communication: A.B. Watson, L. Silverstein, eds. MIT Press, 1992.

"The significance of Eye Movement and Image Acceleration for Coding Television Images," M.P. Eckert and G. Buchsbaum, prepared for Visual Factors in Electronic Image Communication: A.B. Watson and L. Silverstein, eds., MIT Press, 1992.

5. ADVANCED DEGREES AWARDED OR PLANNED

M.P. Eckert , Ph.D. "Spatio-Temporal Image Coding in the Visual System" Awarded 1992, Dr. Eckert is presently a NRC Research Fellow at NASA Ames Research Center.

B.S. Levitan, Ph.D. "Direct Computation and Hierarchic Processing in the Adaptive Expanded Retina", expected 1993

S.M. Courtney, "A Biological Neural Network Model for Color Constancy and Color Contrast" Expected 1993.

6. OTHER PARTICIPATING PERSONNEL

Dr. Peter Sterling (retinal anatomy), Department of Anatomy, University of Pennsylvania.

Dr. Leif H. Finkel, Neural Networks Laboratory, Department of Bioengineering, University of Pennsylvania.

Dr. Andrew B. Watson, NASA, (spatio-temporal coding).

7. COUPLING ACTIVITIES/CONFERENCES

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National Research Council Committee on Vision, Workshop on Visual Factors of Electronic Image Communication, Woods Hole, MA, "The Significance of Eye Movements and Image Acceleration for Coding Television Imagery" M.P. Eckert and G. Buchsbaum, prepared for publication of the workshop.

"M and P Cells Are Matched to the Spatio-temporal Image Spectrum Modified by Eye Movements", M.P. Eckert and G. Buchsbaum, 63rd Annual Meeting of the Association for Research in Vision and Ophthalmology. Invest. Ophthal. Vis. Sci. 32, 841 (1991).

"Efficient Image Coding Operations in Space and Color and Their Correlates in the Early Visual System", J.B. Derrico and G. Buchsbaum, 63rd Annual Meeting of the Association for Research in Vision and Ophthalmology. Invest. Ophthal. Vis. Sci. 32, 841 (1991).

"Decomposition of Natural Images by Principal Components as a Design Consideration for the Visual System", G. Buchsbaum and J.B. Derrico. Annual Meeting of the Optical Society of America (1991).

"The Basic Building Blocks of Color Vision: A Generalized View of the Opponent Color Transformation", G. Buchsbaum. Topical meeting on Advances in Color Vision, OSA (1992).

"Biologically-Based Neural Network Model of Color Constancy and Color Contrast," S.M. Courtney, G. Buchsbaum and L.H. Finkel, IEEE Int'l Joint Conference on Neural Networks, vol. 4, 55-60 (1992).

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McGill University, Center for Vision, "Decomposition of Natural Images by Principal Components as a Design Principle for the Visual System" (1991).

Eastman Kodak Co., Image Sciences Laboratory, Rochester, NY, "Spatio Chromatic Image Coding in the Visual System" (1991)

Tel-Aviv University, School of Engineering, "Spatio-Chromatic Image Coding in the Visual System" (1992).

University of Cambridge, Cambridge UK, "The Basic Building Blocks of Color Vision: A Generalized View of Opponent Processing" (1992).

University of Utrecht, Institute for Biophysics, Utrecht, The Netherlands, "Spatiochromatic Coding of Natural Images in the Visual System" (1992).